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Effect of industrial dust deposition on photovoltaic module performance: Experimental measurements in tropical region

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EFFECT OF INDUSTRIAL DUST DEPOSITION ON PHOTOVOLTAIC MODULE PERFORMANCE: EXPERIMENTAL MEASUREMENTS IN TROPICAL REGION

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ABSTRACT

Dust particles accumulation affects photovoltaic module transmittance of photovoltaic solar cell glazing, and thus leading to substantial reduction of conversion efficiency owing to lower irradiance reaching the surface. In this study, the sensitivity of polycrystalline photovoltaic module towards industrial dust deposition was experimentally investigated under the tropical climatic condition of Arusha Region in Tanzania. Dust involved in the study was collected from fertilizer, gypsum, aggregate crusher and coal mines industries. Particle size analysis was done by sieve analysis technique to get different particle size range 20 µm-45 µm, 45 µm – 90 µm and 90 µm-180 µm. The dust was uniformly distributed over the module with a baby powder bottle which had 100 g capacity with six holes of 0.1 inch diameter size, the holes was covered with sieve mesh in front of it in order to enhance uniform distribution. The experiment was conducted in an outdoor environment whereby two identical polycrystalline modules of rated power 100 W; were mounted at 15° facing north. Each module was connected to digital voltmeter and ammeter, modules current and voltage were monitored by supplying power to a rheostat, the I-V curves measurements were conducted at three different solar irradiances 720 W/m^2, 800 W/m^2 and 900 W/m^2; characteristic electrical parameters were obtained. Results indicate that dust deposition has more effect on short circuit current and does not affect open circuit voltage. Maximum module efficiency loss on polycrystalline photovoltaic module was determined to be 64%, 42%, 30% and 29% for coal, aggregate, gypsum and organic fertilizer dust, respectively. Therefore the coal dust was observed to have higher photovoltaic efficiency loss (64%) compared to all four tested dust samples. It was also demonstrated that photovoltaic module performance deteriorated with temperature rise owing to heat dissipation caused by dust accumulation. In accordance with literature data this study confirmed that efficiency loss on photovoltaic module also depended on the size of the dust particles accumulated on it; small particles reduced more performance efficiency compared with the larger particles.

Keywords: Photovoltaic module, Performance efficiency, Dust, Solar irradiance.

DECLARATION

I, YOTHAM ANDREA do hereby declare to the Senate of The Nelson Mandela African Institution of Science and Technology that this dissertation is my unique work and which has not submitted anywhere for degree award in any other institution.

Name and signature of candidate Date

The above declaration is confirmed

Prof. Tatiana Pogrebnaya

Name and signature of supervisor 1 Date

Name and signature of supervisor 2 Date

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CERTIFICATION

The signatories certifies that they have read and hereby indorse for acceptance by The Nelson Mandela African Institution of Science and Technology a dissertation entitled; *Effect of industrial dust deposition on Photovoltaic module performance: Experimental measurements in Tropical region*, in fulfillment of the requirement for the degree of Masters of Science in Sustainable Energy Science and Engineering (SESE) of the Nelson Mandela African Institution of Science and Technology.

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LIST OF ABBREVIATION

CNH	Carbon nitrogen hydrogen
G	Solar irradiance
I_{mp}	Current at maximum power
I_{sc}	Short circuit current
η	Efficiency
η_{clean}	Clean module efficiency
η_{dirty}	Dirty module efficiency
P_{max}	Maximum power
PV	Photovoltaic
P-V	Power voltage curve
Rh	Relative humidity
T_a	Ambient temperature
T_{noct}	Nominal operating cell temperature
V_{oc}	Open circuit voltage
V_{pm}	Voltage at maximum power
XRF	X-ray fluorescence

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Worldwide climate change, energy security and potential exhaustion of fossil fuel reserves have attracted renewable energy technologies development (Bos & Gupta, 2018; Kirmani, Jamil & Akhtar, 2018). Approximately 80% of energy consumption in the world is from fossil fuels which significantly contributed to climate change (Joseph, Pogrebnaya & Kichonge, 2019). Application of renewable energy technology is valuable due to less impact on environmental degradation as well as the availability is unlimited (Torres, Nashih, Fernandes & Leite, 2018). Away from being sustainable, solar energy system symbolize the most favourable renewable energy resources (Bonkaney *et al.*, 2017). Solar energy harvesting through the use of photovoltaic (PV) systems for the production of electricity is well thought-out as one of the potential markets in the field of renewable energy (Khan & Arsalan, 2016; Obeidat, 2018). Electricity production through the conversion of solar radiation into electricity materializes as a result of photovoltaic effect (Rappaport, 1959; Singh & Gupta, 2019). Energy conversion through the use of PV technologies does not cause serious environmental challenges as compared to conventional power generation sources, such as fossil fuels (Su *et al.*, 2018). The present conversion efficiency of PV systems is approximated at different efficiency ranging between 7 - 40% (Debbarma, Sudhakar & Baredar, 2017).

Photovoltaic systems operations encompass structures such as battery type, module technology and converter topology. Despite these features, PV operation is exposed to environmental condition such as radiation, temperature variations, shading, wind and dust deposition among others (Adıgüzel, Özer, Akgündoğdu & Yılmaz, 2019; Anjos, Melício, Mendes & Pousinho, 2017; Darwish, Kazem, Sopian, Alghoul & Alawadhi, 2018). Climate change contributes to sunlight availability variation causing rises in air temperature, which may always affect performance efficiency of the PV module. Thus, for this reason, solar tracking technology has emerged to assist PV systems in capturing maximum solar irradiance thus an increase of power output (Hammoumi, Motahhir, Ghzizal, Chalh & Derouich, 2018; Ikedi, 2019). Dust is among of environmental constraints that affect the performance efficiency of PV modules worldwide output (Paudyal & Shakya, 2016; Rajput & Sudhakar, 2013; Vidyanandan, 2017). The smallest particle size of less than 500 µm is termed as dust (Pan, Lu & Zhang, 2019; Tanesab, Parlevliet, Whale & Urmee, 2019). Morphological structure, composition and deposition of dust always depend on location characteristics (Aïssa, Isaifan, Madhavan & Abdallah, 2016). Reduction in PV modules performance highly depends on particle size and surface density of dust deposited over the modules (Styszko *et al.*, 2019). Deposition of dust on a panel influence solar cell to heat up whereby affected cells will acts as resistance to the generated current, this tendency may lead to a hot spot that can ultimately damage the PV module and therefore substantial degradation of conversion efficiency (Abdsalam & Ghazi, 2013). Due to minimal interparticle distance between fine particles, a small amount of solar radiation can pass through, hence it reduces more performance efficiency of a module compared with the larger particles. (Hachicha, Al-Sawafta & Said, 2019; Lu & Zhao, 2018).

There are existing studies presented on the impact of dust on solar PV performance, but abundant of the results available is only valid for a particular location (Sulaiman, Hussain, Leh & Razali, 2011). Generally, there is a lack of relevant information on the effects of soil dust deposition for a specific location in Tanzania that can be effectively utilized in the design and sizing of PV modules. Deposition of dust on PV panel blocks solar radiation from reaching cells through the solar panel glass cover. Density, composition and particle size distribution of accumulated soil dust have been shown to have a substantial impact on power produced by hindering solar radiation from reaching the cells through the glass cover of the panel (Aïssa, Isaifan, Madhavan & Abdallah, 2016). Unawareness of the soil dust effect might bring to improper maintenance of solar PV systems and loss of some energy.

This study aimed to experimentally examine the performance degradation of PV modules output power caused by a different type of industrial dust deposition. In achieving its objectives, the study estimated the impact of dust from manufacturing and mining industries. The study will provide information on the effects of industrial dust deposition over the PV modules, which will help users in better maintenance of the system and gain more power output.

1.2 Statement of problem

Though previous studies regarding the effect of soil dust deposition on the PV modules have been done, there are few studies carried out specifically for Tanzania on the effect of dust accumulation on the PV module. There are existing studies presented on the effect of dust on solar PV performance, but much of the information available is only valid for a particular location (Darwish, Kazem, Sopian, Al-Goul & Alawadhi, 2015). Generally, there is a lack of relevant information on the effects of soil dust deposition for a specific location in Tanzania that can be effectively utilized in the design and sizing of PV modules. Deposited soil dust on a cell acts as resistance to the current generated, thereby causing it to heat up and cause to a hot spot which ultimately damage the PV module and therefore substantial degradation of conversion efficiency (Abdsalam & Ghazi, 2013).

Deposition of dust on PV panel blocks solar radiation from reaching cells through the solar panel glass cover. Density, composition and particle size distribution of accumulated soil dust have been shown to have negative effect on power produced by hindering solar radiation from reaching the cells through the glass cover of the panel (Aïssa, Isaifan, Madhavan & Abdallah, 2016). Unawareness of the soil dust effect might bring to improper maintenance of solar PV systems and loss of some energy. Therefore this study aims to deliver valuable statistics for PV module users on the effects dust type, particle size from manufacturing and industrial dust deposition for better maintenance of the system and gain more output power from the PV system. In achieving its objectives, the study estimated the impact of dust from manufacturing and mining industries. The study will provide information on the effects of industrial dust deposition over the PV modules, which will help users in better maintenance of the system and gain more power output.

1.3 Rationale of the study

This study provides useful information to solar PV system users and installation companies on the effects of dust accumulation on PV modules from the mining and manufacturing industries. The study was conducted in tropical region Arusha, Tanzania, where industrial development is rapidly growing as well as the utilization of solar system increasing, therefore there is a need for PV system users to have baseline information about the impact of dust deposition on PV module. Being aware of the impact of soiling on PV system solar users will enhancing the cleaning frequency of the PV modules which will restore energy that would be lost due to soiling. Thus, the output of this study has a direct influence on operation and maintenance (O&M) of the PV module system.

1.4 Objectives

1.4.1 Main objective

The main objective of this study is to experimentally investigate the performance degradation of photovoltaic modules caused by a different type of industrial dust deposition.

1.4.2 Specific objectives

i. To estimate the impact of dust type from manufacturing and mining industries on solar photovoltaic performance.

ii. To estimate the impact of dust particle size on solar photovoltaic performance efficiency.

1.5 Research questions

i. How does dust type from manufacturing and mining industries affect the performance efficiency of a photovoltaic panel?

ii. How does dust particle size affect the performance efficiency of a photovoltaic panel?

1.6 Significance of the study

This study will help to provide useful information that can be used by researchers and installation experts in the design and sizing of PV modules based on the understanding of dust accumulation and the corresponding efficiency reduction characteristics. The study output will provide vital information to installation experts on how to enhance PV module performance and therefore minimize their degradation as a result of industrial dust accumulation.

1.7 Delineation of the study

The delineation of the study was based on environmental factors which affect PV module performance efficiency degradation. Dust being among of those factors, it was selected for experimentally investigation in tropical region Arusha, Tanzania. Dust were collected from different sources manufacturing and mining industries (Organic fertilizer industry, Gypsum industry, Coal mining and Arusha aggregate crusher). Particle size analysis for the collected dust was conducted to obtain three different particle size ranges (20-24 µm, 45-90 µm, 90-180 µm) and chemical composition analysis of the sample was also performed. All three particles ranges of the collected dust type were artificially deposited at a fixed mass (10 g) on one of the two PV modules having same electrical characteristics whereby one of the module was left clean as a control. The test was outdoor conducted at three different solar irradiance 720 W/m^2, 800 W/m^2 and 900 W/m^2, then output power degradation was determined for each of the test.

CHAPTER TWO

LITERATURE REVIEW

2.1 Photovoltaic module performance

Photovoltaic system performance is assessed by measuring the total output energy generated over a given period. Energy generated per power unit is widely used as a judgment parameter within different energy technologies, installation options, alignments, and system stability. Energy generated is also encountered to be one of economic sign that describes the amount of PV modules that have generated for a certain period of time. The price of energy and other reimbursements are assessed to calculate the quantity of energy which will be generated by a PV system in a certain environment (Qasem, 2013). The performance of PV power output is influenced with available solar irradiance which is dependent on energy generated by the PV module at a certain period of time in a given area. Module orientation also influences the energy yield from the PV module, and it is advised to mount the module towards solar tracker to be always directed towards the sun. In practice, it is common to mount the modules on its supporting base keeping them at inclined angle from horizontal which will be the same with the site latitude angle, whereby it may provide good capturing of sunlight. The operating temperature coefficients of PV module changes with operating module rating temperature coefficients. Current electricity and voltage produced by the module are independently influenced by the module operating temperature. The rise in temperature causes the current to increase whereby voltage decreases, performance and energy production decrease when cell temperature rises to above 25 ^{o}C (King, Boyson & Kratochvil, 2002). Not only that but also the performance of PV solar systems are extremely affected by different environmental factors which may be solar radiation intensity, shading, temperature, wind, and pollution (Hussain, Batra & Pachauri, 2017).

2.2 Phenomenon of dust deposition on photovoltaic modules

Soil dust shows a substantial role in the determination of the PV energy production this contributes great impact on the performance of the PV module. This occurs by reducing incoming solar irradiance on the surface of the PV module and varying solar spectrum, which affects PV modules efficiency energy yield (Qasem, 2013; Santhakumari & Sagar, 2019).

Independent or combined effects frequently affect PV system performance. Figure 1 explains factors which influence dust settlement on PV panel.

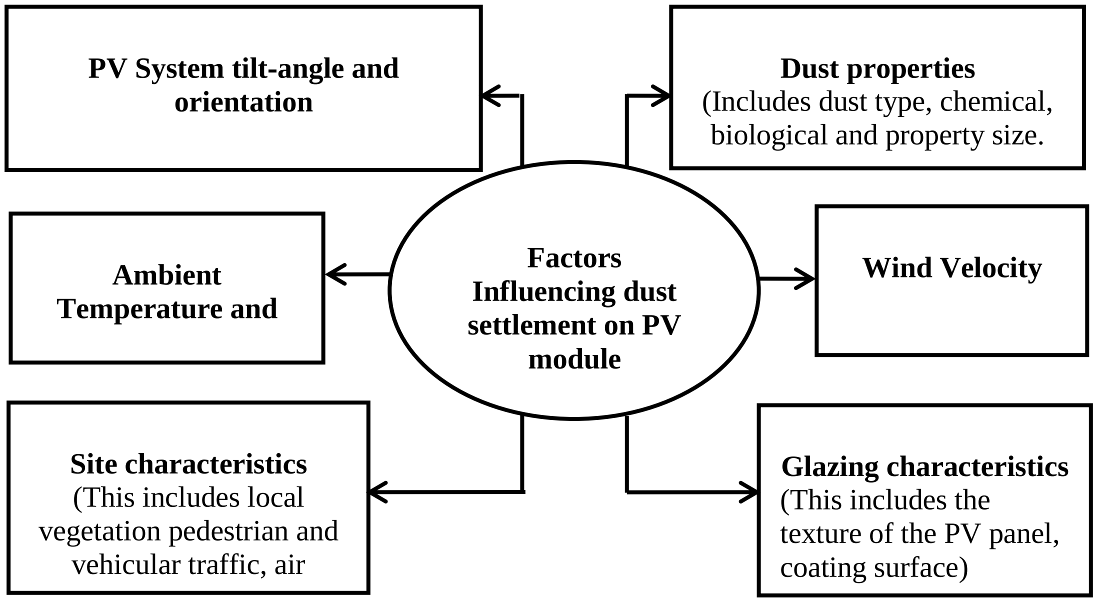


Figure 1: Factors influencing dust settlement (Saravanan & Darvekar, 2018).

Dust is the smallest particles below 500 µm size (Pan, Lu & Zhang, 2019; Tanesab, Parlevliet, Whale & Urmee, 2019). The particles may occur in the environment from different sources which may be resulted from human and nonhuman activities such as constructional sites, industries, agricultural activities, mining activities and dust storm (Hussain, Batra & Pachauri, 2017). Figure 2 describes dust accumulation situation for the PV experimental setup located at the Science and Technology Park, in Doha (State of Qatar) with various PV technologies mounted to observe the performance efficiency and reliability of the system in Qatar climatic conditions.

Figure 2: (a) PV modules after scheduled cleaning and (b) PV modules after dust storm inducing soiling (Aïssa, Isaifan, Madhavan & Abdallah, 2016).

Accumulation of dust is mainly affecting the visual properties of the PV panels, which reduces the generated output power (Abderrezek & Fathi, 2017). It is essential to measure the impact of soiling matching to optical losses. Several researchers have been published in the impact analysis of soiling on the visual properties of PV in dissimilar location in the world (Aïssa, Isaifan, Madhavan & Abdallah, 2016). Table 1 shows different studies on the impact of dust on the performance efficiency of PV modules from a different location in the world.

Table 1: Studies were done on the effect of dust on PV performance at different locations in the world.

Authors	Location	Working condition	Key findings
Hussain *et al*., (2017)	India	Detailed analysis on air dust particle effect on photovoltaic module performance.	Due to dust deposition over the PV modules power efficiency was dropped by 60%.
Ndiaye et al., (2014)	Senegal	Assessment of performance reduction of photovoltaic modules after few years of operation in a tropical environment.	Power reduction performance of PV modules per year was found to be between 0.3% and 2.96%.
El-Din *et al*., (2013)	Egypt	The effect of deposition of air born suspends on PV cell in harsh matters climates located close to the sea.	Dust deposition density increased from 0 to 0.36 mg/cm2, the Performance PV efficiency reduced up to approximately 18%.
Chaichan *et al*., (2015)	Iraq	The effect of Iraqi winter outdoor pollution and dust conditions on PV yield.	A short period of exposure to air dust reduces the PV yield by 12%.
Kazem *et al*., (2016)	Oman	Physical properties of dust from six different locations.	Dust with particles size from 2 to 63 μm in diameter did not contribute any significant of energy loss. Outdoor conditions by 3 months of exposure reduce efficiency by 30-35%.
Adinoyi and Said, (2013)	South Algeria	Performance evaluation of sandstorm deposition on the outdoor environment.	Deposition of sand dust on the surface of PV modules reduces the maximum output power from 29 to 31%.
Hachicha, (2019)	United Arab Emirates	Indoor and outdoor experimental measurements.	The study did show that dust deposition increased by 37.63%, 14.11% and 10.95% when the clean module was inclined at 0°, 25° and 45 respectively. Experimental measurement at outdoor environment revealed that dust deposition increased by 12.7%, while for a period of five months dust density was increased by 5.44 g/m2.
Zitouni, (2019)	Morocco	Outdoor environment, six-month exposure without cleaning	The difference in performance ratio (ΔPR) indicates that a maximum of 16% was observed for a dry period and 2% for the rainy season.
Gholami, (2018)	Iran	Outdoor experimental setup	For 70 days of exposure without cleaning dust deposition density was 6.0986 (g/m2) on the PV module surface, which makes 21.47 % output power reduction.

The impact of dust increase on the PV performance is also argued by highlighting its influence on the current-voltage (I-V) curve characteristics.

2.3 Environment and weather conditions

Accumulation of dust particles on a panel is stimulated by high relative humidity, precipitate formation due to humidity which leads to dust cementing on PV surfaces. Air movement transport soil particles from a different place and deposited it onto PV module surfaces. Carriage mechanisms are of different ways such as turbulent diffusion, sedimentation, inertial forces, Brownian diffusion, and electrical migration. When dust particles come across with a surface, an electrostatic charge often makes earlier accumulated charged particles to result in Coulomb force of magnetism behaviour (Zaihidee, Mekhilef, Seyedmahmoudian & Horan, 2016).

Attraction force will deposit more soil particles, whereby repulsion forces will make the particle to be brown in the air by wind. Wind stream may stimulate dust accumulation based on the PV module installation angle and orientation with relative to wind speed and direction. Moreover, wind speed may accelerate dust accumulation and sedimentation, dust accumulation caused by high wind speed has a high deposition layer than that caused by low wind speed. In the other hand wind speed also can reduce PV cell temperature by acting as cooling mechanisms for PV cell surface temperature. This has shown in Fig. 3 it the trend describes that wind speed is inversely proportional with PV cell temperature this means as wind speed also increases the panel cell temperature decreases (Aly, Ahzi & Barth, 2019). In scenario wind speed acts as a cooling mechanism on PV cell surface heating temperature.

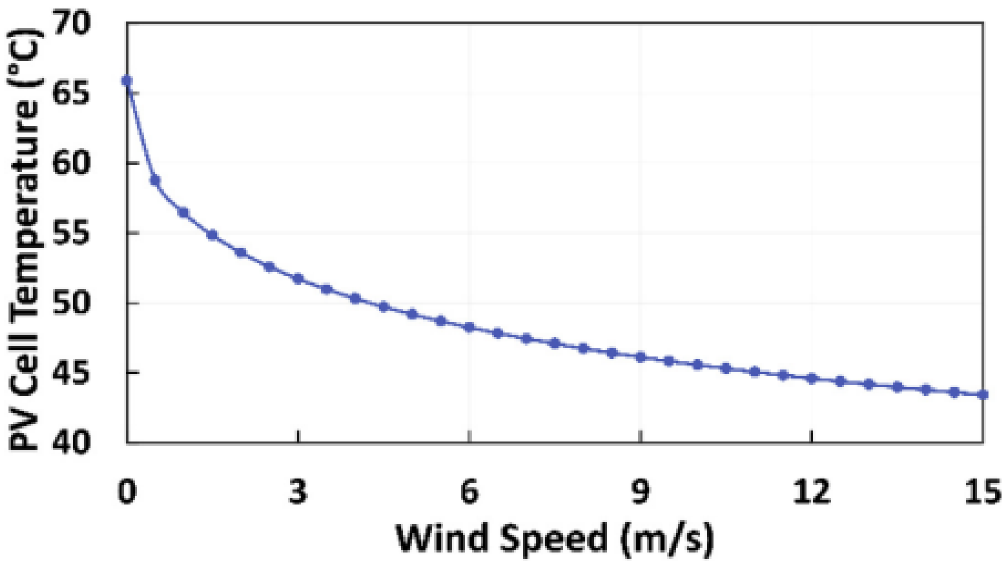


Figure 3: Effect of wind speed on the PV cell temperature (Aly, Ahzi & Barth, 2019).

The rain influences cleaning the polluted PV modules with dust particles as a result of long dust deposition during a dry season. Figure. 4 shows soil accumulation builds up layer which can be removed away by rain. Moreover, this type of soil accumulation reaches a maximum at the dry season and minimum during rainfall season. It has seen that rainfall pattern plays an essential role in removing deposited dust on the PV module (Zaihidee, Mekhilef, Seyedmahmoudian & Horan, 2016).

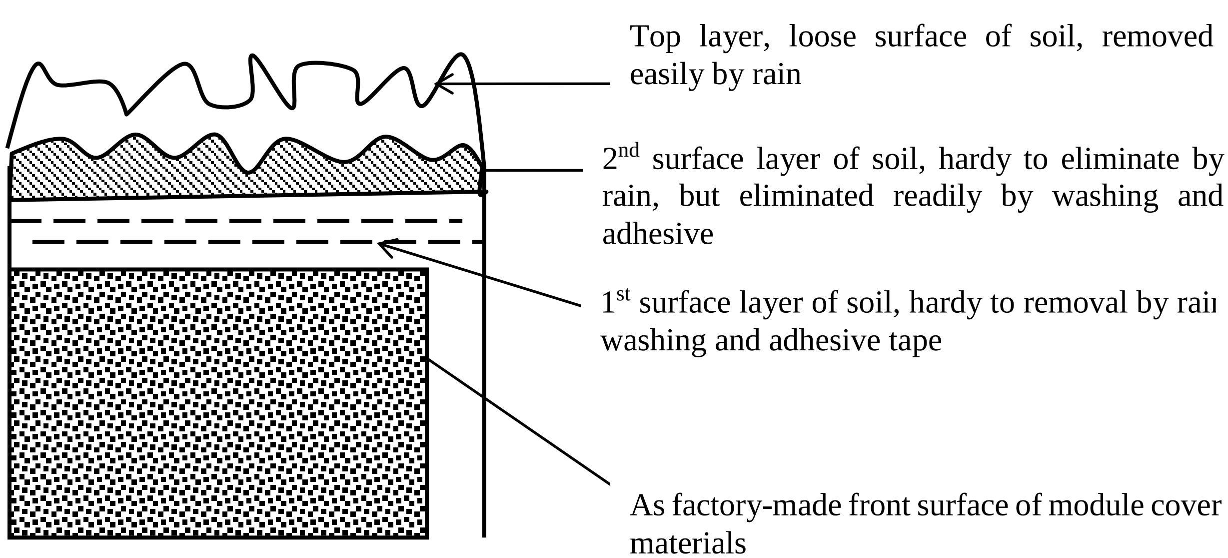


Figure 4: Soil dust accumulation layers (Zaihidee, Mekhilef, Seyedmahmoudian & Horan, 2016).

Rain creates better patterns of dust adhesion on a PV panel in the circumstance of panels covered with severe dust. The situation occurs after a small extent of rainfall passes which always turn dust accumulation into the mud. In this case, more dust will be attracted that will need more extensive cleaning. More heavy rain frequently swept more soil dust pollutants in runoff phenomena, whereby a considerable amount of dust deposited will be thrown away from the module surfaces (Kazem & Chaichan, 2019).

Moreover, the selection of PV mounting configuration has impact on cell working temperature of a panel, the module which is closely installed near the ground surface it usually experiences no airflow at its bottom surroundings. Under typical practical condition there is high-efficiency drop at this configuration condition. Thus solar designer must always consider a recommended minimum distance of 150 mm (or 6 inches) between the rooftop and the PV module in order to allow air movement across the panel rear surface to facilitate cooling effect (Aly, Ahzi & Barth, 2019).

2.4 Effects of dust particle size distribution and chemical composition on the performance of photovoltaic modules

2.4.1 Particle size distribution

Sulaiman (2011) investigated the cement particles sizes density (at 73 g/m^2) which shows that 80% was substantial short circuit voltage drop, this was an indication that the smaller dust particle size for a certain accumulation mass to volume ratio, the higher might be the decrease in solar radiation falling on a PV module (Sulaiman, Hussain, Leh & Razali, 2011). The impact was influenced by the higher aptitude of smaller size particles to reduce the gap between particles, therefore hindering the intensity from passing among them compared with larger dust particles. A study conducted at Saud Arabia on dust particle size with similar properties but different size particle with the same densities, the particles lead to a diverse impact on the PV panel power output. Limestone sample of different particle size distribution with deposition density of 100 g/m^2 was investigated. The tested sample shows different results with respect to its particle size. Size particle diameter of 80 µm, 60 µm, and 50 µm yields short-circuit currents of 0.53 A, 0.37 A, and 0.29 A respectively. The results indicate that the fine particle size of given dust has a more significant impact compared with the coarser particle. The results define that finer particles can minimize inter-particle spacing whereby light can pass through. Therefore efficiency of the PV cells is affected more by fine dust accumulation over the surface compared with a similar deposition of larger particles (El-Shobokshy & Hussein, 1993).

2.4.2 Chemical composition

Presence of chemical elements in dust type has a substantial effect on PV modules output power. Availability of alkali and alkaline earth metals in the soil causes dust to solidify in water under humidity condition to form a solution which is chemical in nature at the PV glass surface. This solution formed will change the surface texture of glass, by doing, so it increases the micro solidity and reduces the transmission of the incident optical radiation. The removal of mud created at the glass surface is difficult due to high cohesive forces formed from the dried mud. The capability of changing characteristics of PV glass surface is an indication of restrictions of shielding surfaces has consequences for solar system efficiency.

Yilbas *et al.* (2015) stated that transmittance may drop nearly to 35% (on average), for mud accumulation on the glass surface. Drop on PV power output is associated with light transmittance reduction, soil residues, which hinder the incident light radiation. Mud deposited from the dust at PV glass surface significantly accelerates absorption properties, transmittance properties, microhardness properties, and surface texture behaviour of glass. Mud generated from alkali and alkaline earth compounds are associated in the form of a chemical solution, these solution stockpiles between mud and glass interface due to gravity. Presence of alkali and alkaline hydroxides in the mud solution pH rises approximately to 8.4 (basic). When mud solution attack glass surface it alter the surface texture whereby diffusion of the chemical solution at the surface region causes microhardness of the glass surface whereby it reduces optical light transmittance (Yilbas *et al.*, 2015).

2.5 Soil shading effect on photovoltaic performance

Increase of leaves, dirt, pollen, bird droppings and snow on PV arrays may decrease the efficiency of a module by increasing power losses as the number of dust increases. Therefore, deposition of dust on solar panel can cause substantial reduction in the energy produced. This condition becomes poorer in some operating environment of PV module, the occurring circumstances like snow deposition on PV modules always might cover the panel surface completely, and no power will be generated (Maghami *et al.*, 2016). The effect of uniformity soiling is as the situation of dragging a window screen throughout the PV array or minimizing the genuine solar irradiance falling on it. The general form of the current-voltage curve is correct, but the charge flow at different voltage is minimized which is contributed by unequal distribution of the soil. In real sense low-tilt angle of PV array usually cause soil dust to extend from down edge of a module to upward when this deposition spreads up to the bottom row of cells the I-V curve is always reduced (Gurupira, 2018).

2.5.1 Partial shading of the photovoltaic module

Energy decrease in PV modules due to deposition of dirt or soiling effect on the array surfaces, it always hinders some solar cells to capture solar irradiance. This contributes to severe impact on PV modules power generation, by considering Fig. 5, which consists of 10 cells and one of them being shaded, and it has no ability to generate any current. Therefore, as Fig. 6 illustrates this situation, the covered cell creates typically resistance to the current produced from other cells. The situation results in heating to the covered cell and resulting in a hot spot which may ultimately damage the PV module (Maghami *et al.*, 2016).

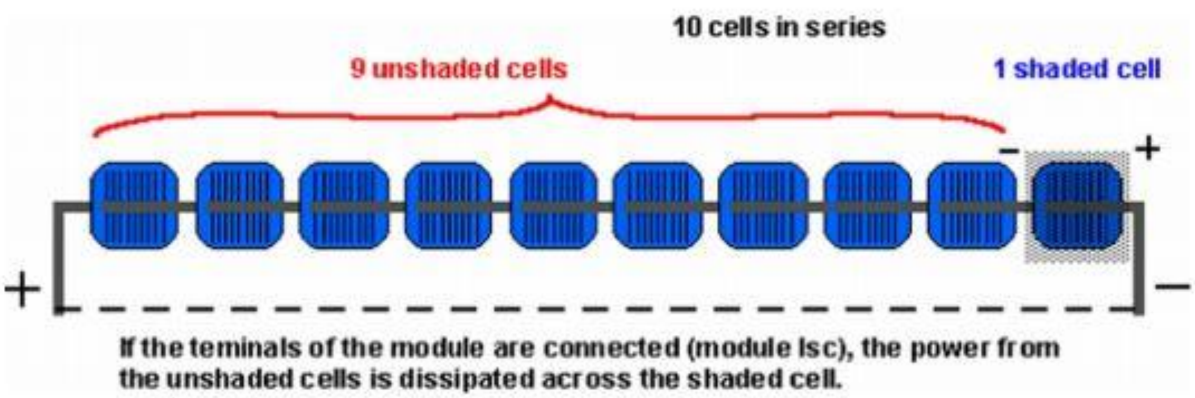


Figure 5: Current flow through shaded cells (Maghami *et al*., 2016).

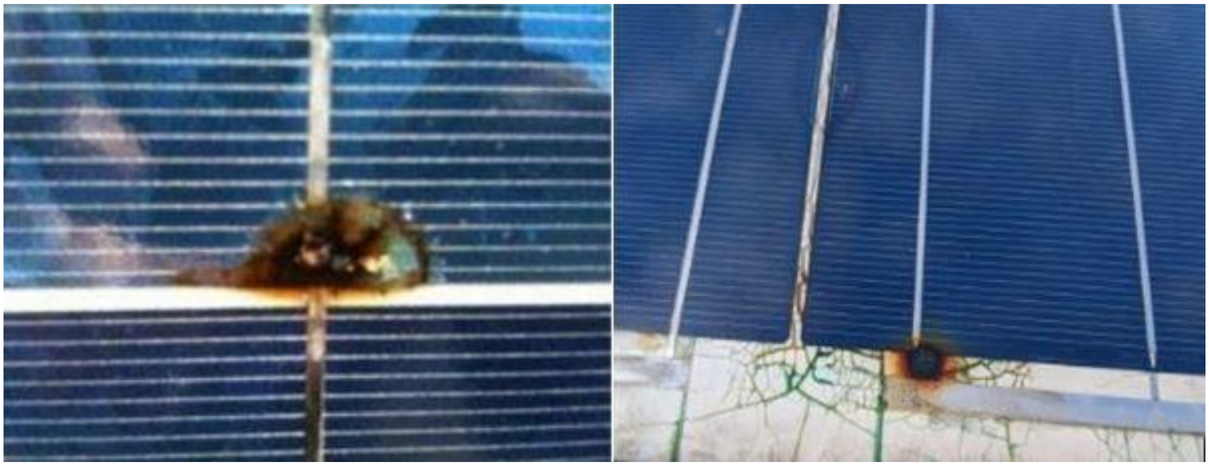


Figure 6: Affected PV module due to cell hot spot (Olalekan, 2019).

2.5.2 Photovoltaic module power reduction due to shading/dust effects

Current voltage curve of a PV module below, illustrate the ability of a panel to transform the solar energy at a certain solar irradiance and temperature. Short circuit current from the current-voltage (I-V) curve varies from short circuit current (I_{sc}) at an open-circuit voltage (V_{oc}) at zero current value to a voltage of zero value as verified in Fig. 7 below (Weldemariam, 2016).

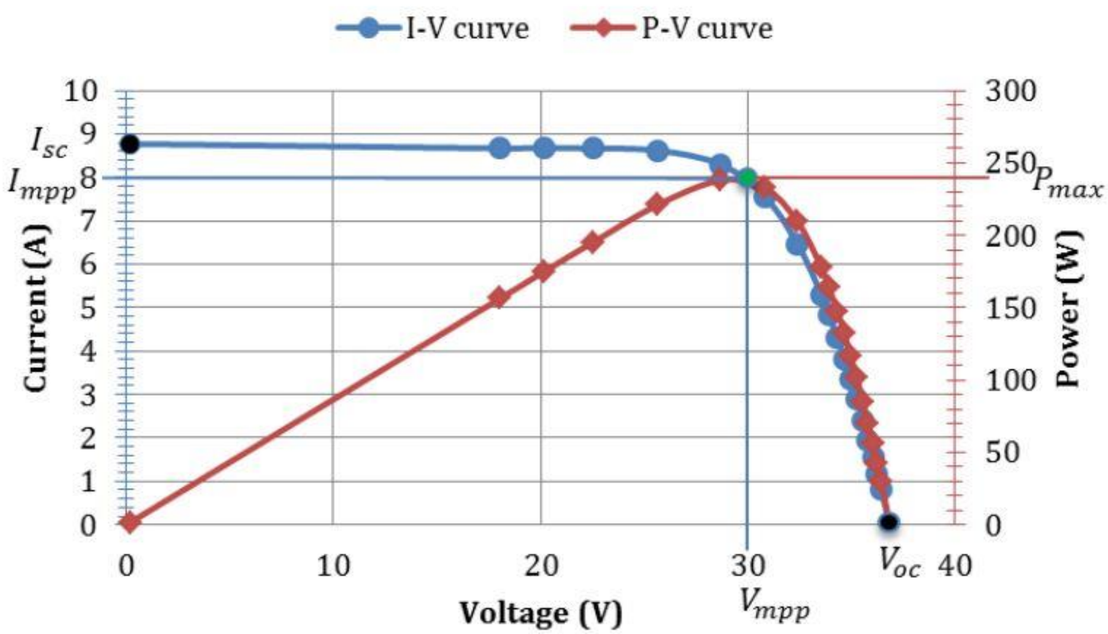


Figure 7: Polycrystalline module P-V and I-V curves with their curve's main points (Weldemariam, 2016).

In Fig. 7, current at maximum power (I_{mp}) and voltage at maximum power (V_{mp}) indicate where now the product of the two points occurs is recognized as a maximum power point (P_{max}) of the system. Usually, the power generated from PV modules is less compared with the total power of the values produced from individual power cells, this occurs due to the dispersion of the parameters. The losses are emphasized due to partial or full shadow condition from one or more cells consecutively connected to form PV module. Impact of shadow on solar radiation intensity leads into reduction of PV module power generated. The evaluation was done for shadow rate of a single solar cell with a module formed by several solar cells connected in series. Single-cell which is generally shaded it has no significant impact on extreme power loss, it is below 10% at lower solar radiation (Silvestre & Chouder, 2008). Figure 8 illustrates that the power loss increases with the increase of shadow rate.

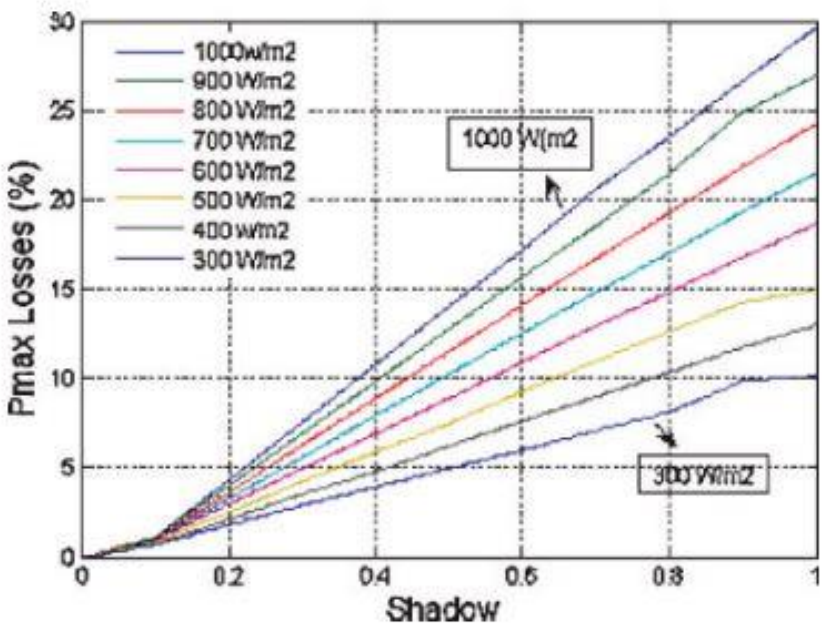


Figure 8: Effect of various solar irradiation and different shadow rate on power reduction (Silvestre & Chouder, 2008).

The impact of dust deposition over PV modules always depends with a time of exposure on reducing the corresponding energy yield. A real world on natural deposition of dust over PV module has experimented, whereby it has observed that more significant power loss occurs on long periods of dust deposition. Moreover, experimental study which was done by the previous researcher indicates significant maximum current reduction to be 6.9% to 16.6% relying on duration of the PV module exposure in dust environment for one day to one month (Saidan, Albaali, Alasis & Kaldellis, 2016). Figure 9 (a) & (b) illustrate the impacts of dust deposition on PV module for daily and monthly exposure time period, respectively.

Impact of dust on PV module performance is governed by unchangeable and changeable factors which are under location-dependent categories basing on environmental characteristics. Soil dust can affect output power of the module into two possibilities, first are those dust suspended into the atmosphere which its size is bigger than the wavelength of incoming solar beam which scatters sunlight which minimizes quantity of incoming solar radiation over the panel. The effects become poor when meets with meet with pollutant in the air. The decrease in PV module output performance of over 60% has been recognized to the presence of dust and air pollutants (i.e. suspended particles and toxic gases) within the atmosphere. The second impact relay to the development of a dense deposit of dust over a PV module surface. The created layer can alter the optical properties of the module surface by making light rays to undergo absorption and reflection and therefore minimize transmissivity, and later reduce module output (Said, Hassan, Walwil & Al-Aqeeli, 2018).

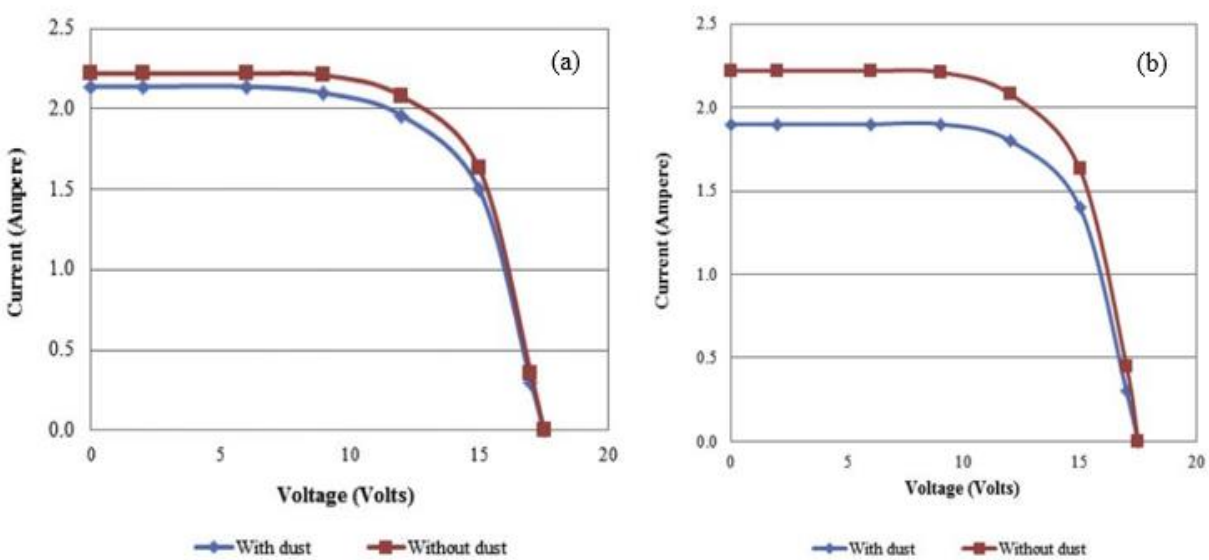


Figure 9: Variation of current to the voltage on the PV module from daily (a) to monthly (b) dust exposure (Saidan, Albaali, Alasis & Kaldellis, 2016).

2.6 Dust distribution over the photovoltaic surface

2.6.1 Dust deposition density on photovoltaic module

Dust particle size accumulation on PV module surface relies on the period of exposure (Mostefaoui, Ziane, Bouraiou & Khelifi, 2019). The study was done for four months of exposure deposition density increases from 1.2 to 2.6 g/m^2. Also the author noted that a significant amount of sand was airborne in the mentioned period of exposure that was the season caused by more frequent sandstorms. After the followed two months dust deposition density increased by 1.05 g/m^2, hence the total value of particle deposition to become 4.85 g/m^2 as depicted in Fig. 10.

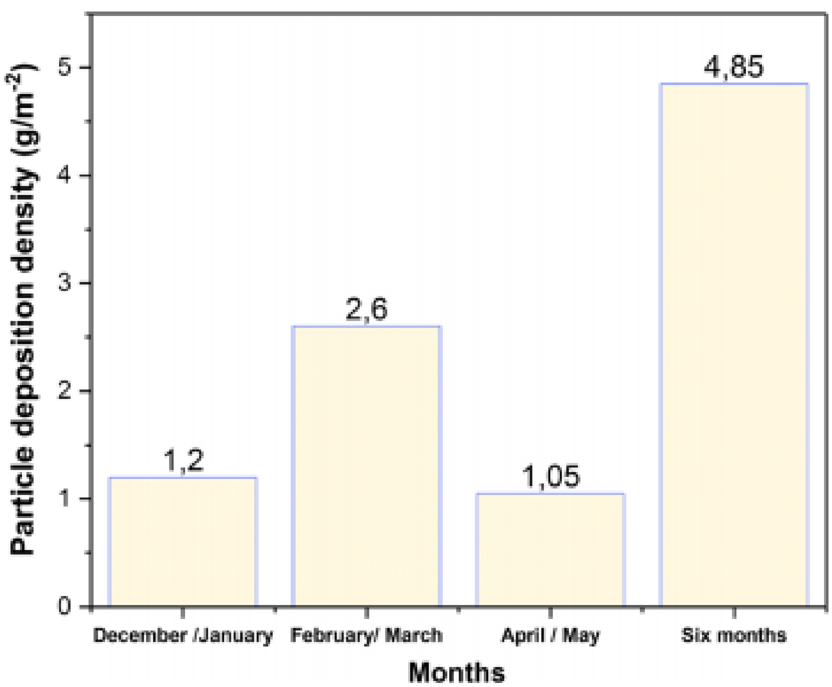


Figure 10: Sand dust deposition densities with an exposure period (Mostefaoui, Ziane, Bouraiou & Khelifi, 2019).

Gholami, Khazaee, Eslami, Zandi and Akrami (2018) reported that the rate of dust accumulation over the solar panel surface at the beginning of the experiment was varying from 0 g/m^2 for clean sample to 6.0986 g/m^2, at the final of the experiment while output power reduction was observed to be 21.47% to the reference cells, as depicted in Fig. 11, which shows that the power loss percentages increase linearly with dust surface density, and ultimately output power reduction occurs. Moreover, the study done by Tanesab, Parlevliet, Whale and Urmee (2019) reported that decrease in performance efficiency is proportional to the amount of dust accumulated over the PV module glazing surface, as the rate of dust sticking on the module surface increases in where now the rate of energy generated decreases. Additionally, Gholami, Khazaee, Eslami, Zandi and Akrami (2018) observed that the output power delivered from the dirty module was deviating from the clean module as time goes. At the final of the experiment 70 days with no rainfall, output power dirty and clean module were 1712.5 kWh and 2001.5 kWh respectively.

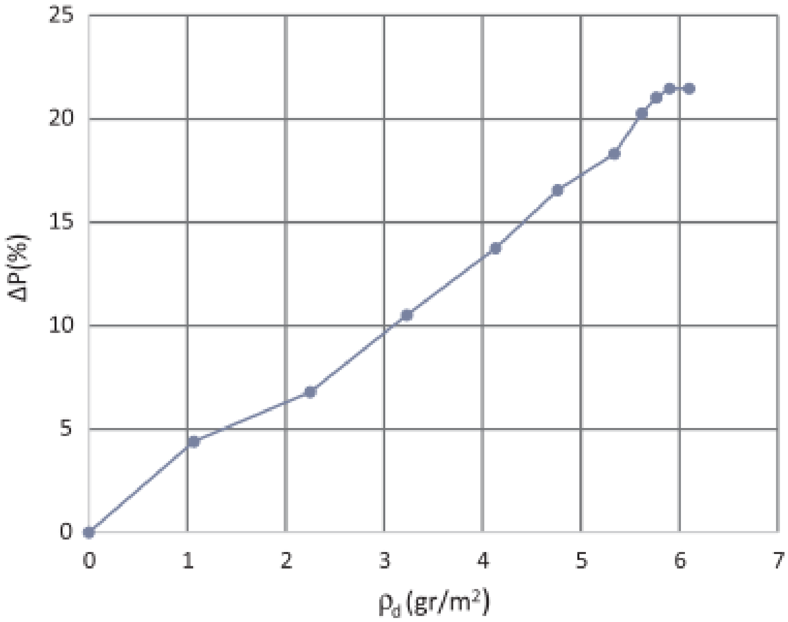


Figure 11: Output power loss against average dust surface density (Gholami, Khazaee, Eslami, Zandi & Akrami, 2018).

2.6.2 Effect of dust deposition density on voltage, current, efficiency and power

The study conducted by Hamdi, Hafed, Chaichan and Kazem (2018b) naturally dust deposited over PV module glazing surface was added to a clear cell for the interval of 10 g until it reaches to 100 g, the aim was to study the impact of dust deposition over the panel surface for 6 hours. The impact of dust deposition density on voltage, current, energy and efficiency were investigated. Figure 12 depicts the changes in the current, voltage, power and efficiency (represented by a, b, c and d) for the cell used in the experimental study, respectively. Different deposition densities were applied, the results depicted 19 V and 5.3 A as the highest voltage and current, respectively, and the highest power and efficiency were 100.7 W and 13.58%, respectively. On the other hand, 4.6 A was observed to be the lowest current value after 100 g of dust deposition over a cell and efficiency was observed to be 13.8%. For the similar scenario the lowest voltage, power and efficiency values were 16.2 V, 74.52 W and 10.05%, respectively, whereby output reduction in voltage, power and efficient was 14.73 V, 25.99 W and 26%, respectively.

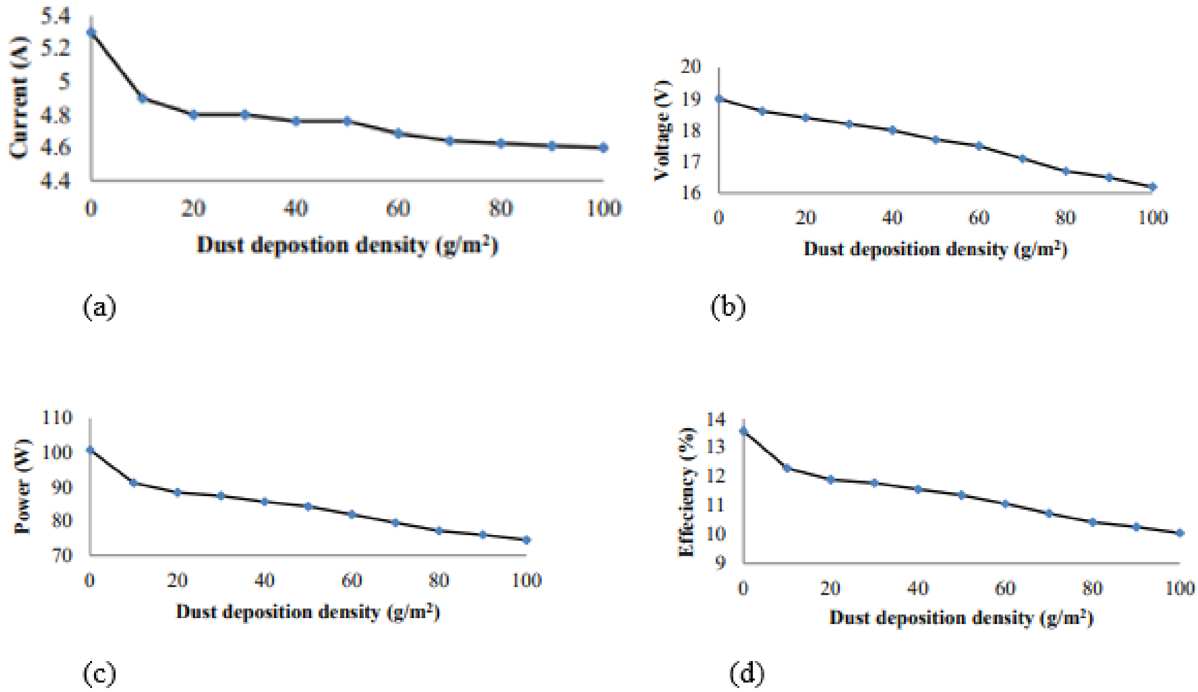
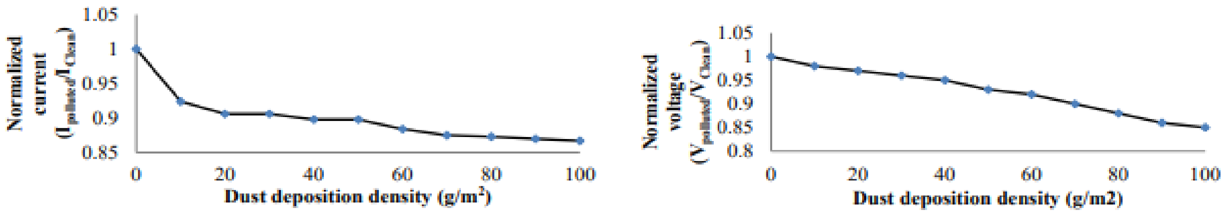


Figure 12: Effect of dust deposition density on current (a), voltage (b), power (c), and efficiency (d) of a PV cell.

The effect of dust on voltage and the current was also investigated by Hamdi, Hafed, Chaichan and Kazem (2018b) as indicated in Fig. 13 in which Fig. represented by a letter (a) describes current ratio for dirty and clean module while that of (b) describes voltage ratio for the dirty and clean cell. The current reduction was about 7.6% from deposition dust density varies from 0 to 10 g/m^2. Reduction rate for voltage was up to 2% for similar situations. The highest current reduction was 13.2%, while 15% was voltage reduction for the similar test condition.



(a) (b)

Figure 13: Current ratio (a) and the voltage ratio (b) for dirty to clean module versus dust density (Hamdi, Hafed, Chaichan & Kazem, 2018a).

Cell efficiency loss from different quantity of dust accumulation on the cell surface was obtained by equation 2.1.

$$\eta_{loss} = \frac{\eta_{clean} - \eta_{dirty}}{\eta_{clean}} \times 100 \quad \ldots\ldots (2.1)$$

Figure. 12 (d), defines that when dust accumulation density increases from 0 to 100 g/m^2, also efficiency generated by the cell decreases from 0 to 26%. Dust deposition over the cell surface has a substantial effect on solar cell performance. Furthermore, randomly dust accumulation on the cell surface is not uniform; it usually varies on the same cell surface (Hamdi, Hafed, Chaichan & Kazem, 2018a).

2.7 Dust characterization

Characterization of dust conducted for the matter of understanding how its behaviour based on chemical composition, particle size may contribute to affect performance degradation of PV module and providing proper mitigation measure to overcome the problem. Characterization approaches comprise chemical composition analysis, particle size analysis and morphology analysis (Said, Hassan, Walwil & Al-Aqeeli, 2018).

2.7.1 Particle size analysis

Several techniques have been used to determine different characteristics of dust, morphology and particle size analysis can be done by both scanning electron microscope and optical microscope technique. Moreover, in recent years, a scanning probe microscope is also used (Said, Hassan, Walwil & Al-Aqeeli, 2018). Previous studies indicate that accumulation of finer particles over the PV modules has higher significance on performance efficiency loss compared with the larger particles (Hachicha, Al-Sawafta & Said, 2019; Javed, Wubulikasimu, Figgis & Guo, 2017). Distribution of dust grain size and optical properties are influenced by morphology factors comprising surface texture and shape (Liu, Park, Schnare, Hill & Taylor, 2008; Mishra *et al.*, 2015). Dust particles with different morphologies may contribute to the magnitude of light refraction. Therefore different shapes may cause substantial light deviation to the range of scattering angle (Tanesab, Parlevliet, Whale & Urmee, 2019).

2.7.2 Chemical composition analysis

Chemical nature of dust have significant contribution in performance efficiency reduction, it may be elemental composition, or color plays significant role in output power reduction by reducing the transmittance degree of the grazing surface of the module and hence decrease in output power yield. Kaldellis, Kapsali and Kavadias (2014) studied various type dust type carbon-based ash, limestone and red soil, on how it may affect the performance of the PV module when particles are accumulated over the panel surface. The author observed that an average output power reduction to vary between 3 W and 5 W for dirty and clean module for the red soil deposition density 0.12-0.35 g/m^2, from 4 W to 7 W for the same particles from red soil but its deposition density varying from 0.28 to 1.58 g/m^2 and 1-8 W power varying when deposition density was varying between 0.63-3.71 g/m^2 respectively. The author concluded that red soil accumulation over the PV module affects the most significant performance and consequently the energy produced by the module followed by limestone and lastly by carbon-based ash. Also, Kaldellis, Kapsali and Kavadias (2014) reported that 7.5% of energy reduction occurred when 0.35 g/m^2 of red soil was deposited over the module, while nearly the same amount of limestone (0.33 g/m^2) when it was accumulated over PV module caused the energy reduction by 4%.

Hachicha, Al-Sawafta and Said (2019) report that composition of minerals in dust sample contains distribution of organic and inorganic particles which involve high and low water- soluble salts. Under the high level of humidity, all mineral particles which are soluble tend to form droplets which are naturally salt that hold all insoluble particles. When it became dried, it undergoes cementing property that grips insoluble particles causing higher adhesion to the PV glazing surface. This situation is known as cementing effects, in which the dust particles sticky at the surface of module and it is difficult to be removed either by wind or rain for smaller particles (below 10 µm). The chemical property of dust causes strong adhesion forces to the photovoltaic glazing surface such phenomena required to be taken into consideration in appraisal of dust removal technique. Moreover, removal technique of applying anti-reflective and ant soiling coating can change the adhesion forces over the top of PV module surface which may have great impact on removing dust.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials used in this study

The experiment was designed and performed to investigate the physical properties of the dust effects of four selected dust samples and their effect on PV performance. Dust samples were collected from the manufacturing and mining industries located in different parts of Tanzania. The four dust samples (Fig. 14) were selected from Organic Fertilizer Industry (Minjingu), Saint Gobain Lodhia Gypsum Industry, Mining Aggregate Crusher located in Arusha city and Ngaka Coal Mining located in Ruvuma- southern part of Tanzania.

Figure 14: Dust sample used for the experimental study: (a) Aggregate crusher dust, (b) Coal dust, (c) Fertilizer industry dust, (d) Gypsum industry dust.

3.2 Dust sample preparation

Particle analysis distribution for the collected samples was conducted at NM-AIST Laboratories. The collected samples were sieved into different particle size ranging from 90 µm-180 µm, 45 µm – 90 µm and 20 µm-45 µm under sieve analysis technique. The method comprised of stowage of the sieve with dissimilar sieve holes, and the smallest sieve was placed at the bottommost of the sieve stack. The technique separates particles from a bigger size to the smallest size according to the sieve arrangement. The sieves are categorized according to the openings, and it is obvious named to sieve number, the sieve used in this study were labelled with sieve number as (#80 µm), (#170 µm), (#325 µm) and (#600 µm). The particle size of the dust sample used in this experimental study was classified into three different particle size ranges (90 µm-180 µm, 45 µm – 90 µm and 20 µm-45 µm). Each sample was weighted by digital weight before putting it on the upper sieve set, then the sieve set was placed on the Retsch sieve shaker, and vibration frequency of 200 Hz was configured, and the Retsch sieve shaker was allowed to start and stop after 15 minutes. After the Retsch sieve shaker completed each sieve were taken to digital weight balance and weighted, then the weight was subtracted from net weight of empty sieve and the mass retained in the sieve were obtained. Individual mass retained in each sieve were divided by the summation of mass remained in all sieves and multiplied by a hundred to obtain percentage weight retained in individual sieve. Table 2 illustrates the experimental average weight percentage (%) for sieve analysis test conducted in the laboratory for different particle sizes.

Table 2: Average percentage (%) weight retained on sieve analysis test.

	Dust sample							
	Fertilizer industry		Aggregate crusher		Gypsum industry		Coal mining	
Sieve particle size (µm)	Weight retained (g)	% Weight retained	Weight retained (g)	% Weight retained	Weight retained (g)	% Weight retained	Weight retained (g)	% Weight retained
180 - 90	140	52.50	40	81.09	141	53.41	20.6	55.98
90 - 45	65	24.37	5.33	10.80	111.67	42.30	10.33	28.07
45 - 20	61.67	23.13	4	8.11	11.33	4.29	5.87	15.95

3.3 Experimental setup

The experiment was conducted in an outdoor environment in which PV modules were mounted at Innovative Technology and Energy Centre within Nelson Mandela African Institution of Science and Technology premises, Tanzania (latitude -3.23^0 S, longitude 36.47^0 E). Two polycrystalline modules of rated power 100 W; were mounted at an inclination angle of 15^0 facing north; electrical characteristics are shown in Table 3. The experiment was conducted to determine the effects of dust deposition over the PV module; four different types of dust collected from different locations were tested to assess its impact on PV module. One module was covered with dust while another module was left clean for output power comparison purposes. Cleaning method of the dirty module maybe with a fine brush (Mostefaoui, Ziane, Bouraiou & Khelifi, 2019), which was also adopted for this study in cleaning the polluted panel. The measurements were performed at clear sky condition during the day, performance degradation assessment for the PV module was done at three different solar irradiances 720 W/m^2, 800 W/m^2 and 900 W/m^2. An experimental study was done based on selected dust particle size from four types of dust. Weight of 10 g for each sample was weighted by digital weight balance. Dust was uniformly distributed over the module with a baby powder bottle covered with sieve mesh in front of it (Fig. 15). Experimental setup depicted in Fig. 17, each module was connected to digital voltmeter and ammeter, current-voltage correlation (I-V) and power voltage correlation and maximum power were examined. Module current and voltage were measured by supplying power to a rheostat (Fig. 16).

Figure 15: PV Module experimental setup.

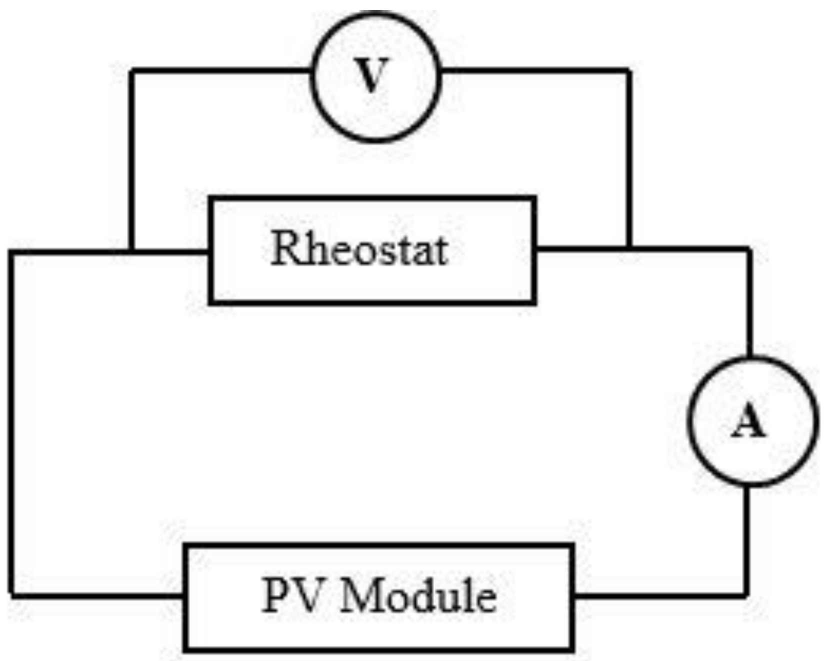


Figure 16: PV module circuit schematic diagram.

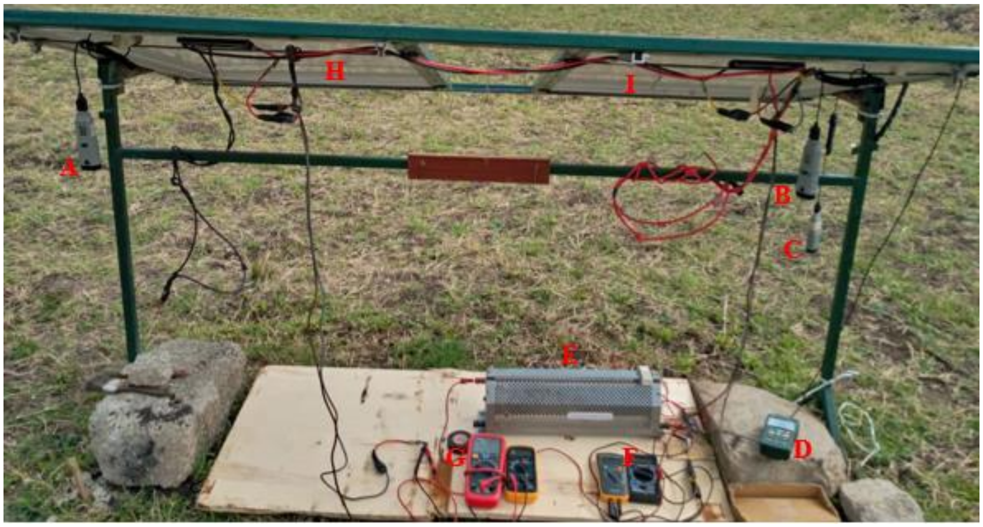


Figure 17: Equipment and accessories details; A, B, C - data loggers with temperature and humidity sensors, D - Solar meter, E – Rheostat, G and F - digital multimeters, H and I - solar panels.

Table 3: PV modules technical characteristics.

Electrical specification	Value
Maximum Power	100 W
Current at maximum power (I_{mp})	5.36 A
Voltage at maximum power (V_{mp})	18.65 V
Short circuit current (I_{sc})	5.71 A
Open circuit voltage (V_{oc})	22.25 V
Nominal operating cell temperature (T_{noct})	45±2 ^{o}C
Module dimension (mm)	1020 *675 *25

The temperature of the modules, relative humidity, ambient temperature and solar irradiance were monitored by USB temperature data logger sensor (SSN-11e) in which the sensor was attached at the back of the panel. The USB temperature humidity data logger sensor (SSN-22e) was left hanging to the environment where the modules were mounted, as well solar power meter data logging sensor (TES 132) was attached on the panel frame with the same installation angle of PV module respectively.

3.4 Data processing and measurements

The experiment was done under three different selected solar irradiances for all four dust samples under particle size range. Instantaneous current and voltage were recorded at real-time condition, the maximum current and maximum voltage also were obtained from I–V curves generated from the experiment and power maximum was attained from the P-V curve. The efficiency of the module depends on several parameters which are maximum power (P_{max}), solar irradiance (G) and module surface area (A), and it may be calculated through the following equations.

$$P_{\max} = I_{mp} \times V_{mp} \qquad (3.1)$$

$$\eta = \frac{p_{\max}}{G \times A} \qquad (3.2)$$

From the individual module efficiency, performance efficiency loss of PV module can be calculated through equation (3.2), by using the relationship (Jaszczur *et al.*, 2018).

$$\eta_{loss} = \frac{\eta_{clean} - \eta_{dirty}}{\eta_{clean}} \times 100 \qquad (3.3)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

Discussion in this section present data acquired from experimental measurement and analysis. The first part is about a variation on the weather condition of the day during experimental measurements on the study area. Photovoltaic module performance, power and current output drop due to dust deposition, PV module efficiency. In the last part, analysis of results is given regarding the effect of temperature, dissimilar types and particle size of dust to PV module performance.

4.1 Variation of weather condition at the site

As described in Fig. 18, during data collection in the study area there was fluctuation of weather condition, i.e. solar radiation, relative humidity and ambient temperature. An experimental measurement in the study area included the mentioned three parameters. It was observed that solar radiation was high from 12:00 AM to 03:00 PM. Moreover, relative humidity was high during the morning time and was decreasing towards noon time, and this indicates that as sunlight intensity also increases relative humidity decreases. However, in this study ambient temperature was increasing from morning towards noon.

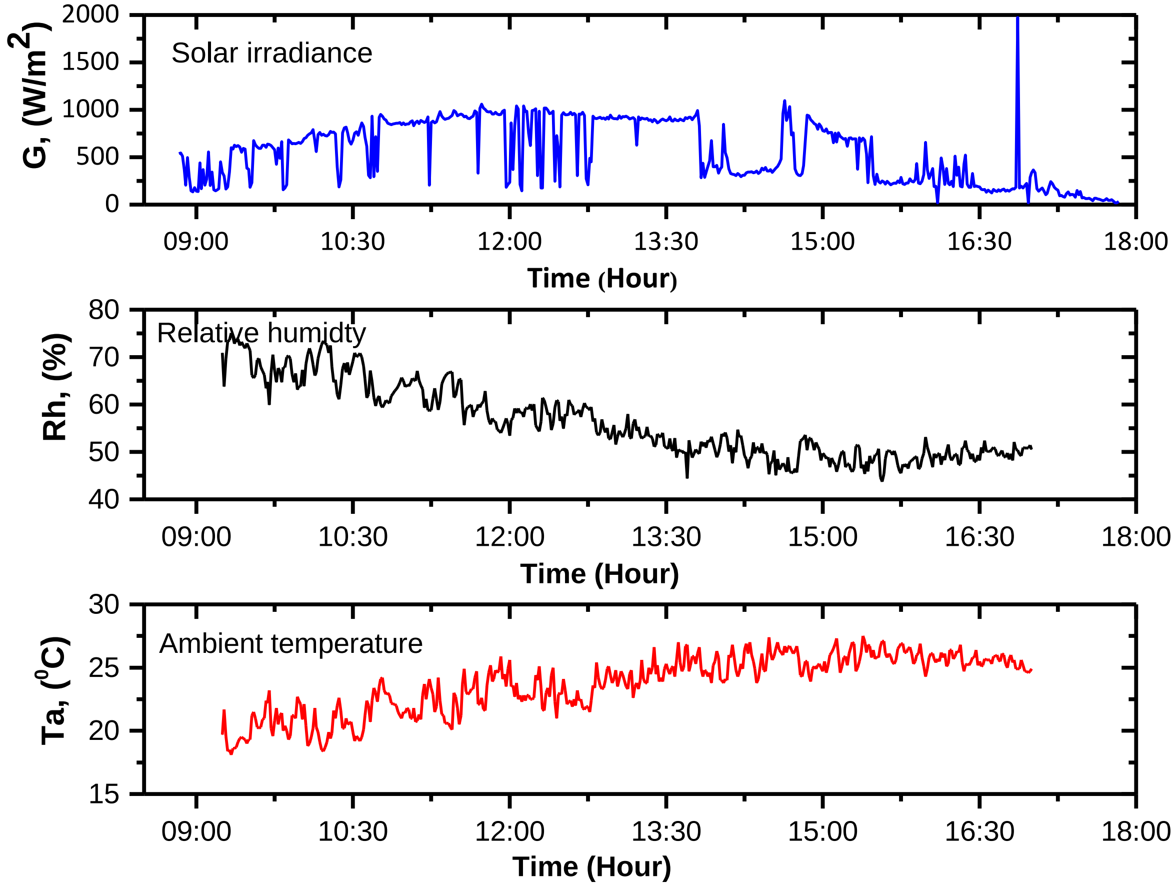


Figure 18: Weather parameters data taken at the site.

Concerning to the ambient temperature and relative humidity, the experimental outcomes of this study has also presented a relationship of energy yield with an increase in ambient temperature and humidity. Increase in ambient temperature causes the rise of module operating temperature, therefore, reducing output energy. This is recognized due to fact that increase in relative humidity influence the rise of water vapour in the atmosphere, so when solar irradiance knockouts water vapour droplets, diffracted reflected or refracted may occur (Bonkaney *et al*., 2017). These effects dive the response level of the path component of the irradiance influence on the power output produced by the PV module. Also, in this study for the measurement taken in June, it has been observed that air temperature was increased by 32.8% while relative humidity reduced by 74.4% as depicted in Fig. 19.

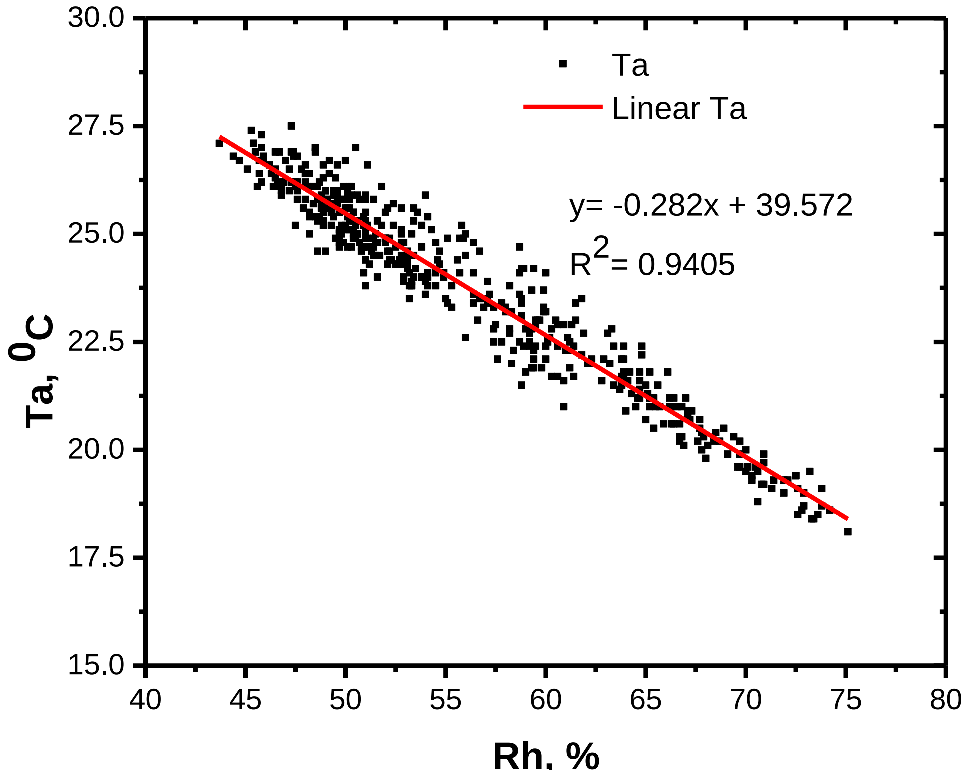


Figure 19: Ambient temperature versus relative humidity on 12 June 2019.

4.2 Photovoltaic power and efficiency loss due to temperature for a clean panel

In this study, power and efficiency losses due to temperature on PV module were investigated, the assessment was done for the clean module. Change in power P_{max} and efficiency yield due to temperature effect at different solar irradiance (720 W/m^2, 800 W/m^2 and 900 W/m^2) were assessed (Table 4). Experimental results proved that temperature rise reduces the P_{max} and module efficiency as well. Minimum and maximum module temperature were observed to be 30.0 ºC and 48.6 ºC respectively, whereby P_{max} raised to 97% of rated power and dropped to the minimum level of 63% accordingly. At G = 900 W/m^2 and T = 30.6 ºC, the P_{max} = 96.7 W was very close to the rated value, and efficiency was also high, η = 15.6%. In average, the power decreased by 1.3 - 1.8 W and efficiency lowered by ~0.3%, per each degree in temperature rise.

Table 4: Temperature effect on a clean module performance.

G = 720 W/m^2			G = 800 W/m^2			G = 900 W/m^2		
T_p (ºC)	P_{max} (W)	η (%)	T_p (ºC)	P_{max} (W)	η (%)	T_p (ºC)	P_{max} (W)	η (%)
30.0	83.8	16.9	37.3	86.0	15.6	30.6	96.7	15.6
31.0	67.0	13.5	42.1	81.0	14.7	32.6	86.2	13.9
31.5	65.0	13.1	48.3	79.4	14.4	39.9	84.3	13.6
42.1	63.0	12.7	48.5	75.0	13.6	40.3	79.4	12.8
46.4	62.5	12.6	48.6	65.0	11.8	41.6	78.8	12.7

4.3 Impact of dust on photovoltaic modules temperature

Dust deposition on the solar panel has also impact to cell operating temperatures. The observation was made during the experimental test when aggregate dust with size particle 20 – 45 µm was deposited over the module, and whereby temperature difference between the clean and dirty module was observed to be varying by between 1 ºC – 9 ºC (Fig. 19). The abrupt rise of cell operating temperature for both modules (at 11:10 AM) is due to the decrease in relative humidity as demonstrated in Fig. 20. Moreover, the increase or decrease in cell operating temperature also be influenced by solar irradiation intensity reaching the panel surface. Our observation about the impact of dust on the PV panel temperature is agreed with the study done by Rao, Pillai, Mani and Ramamurthy (2014) which reported that dirty module temperature was observed to be higher compared with the clean one. Due to dust accumulation, the incoming solar irradiation over the panel tends to be hindered. Deposited dust also avoids heat dissipation to the dirty module (Liu, Yue, Zhou & Sun, 2019). This is the reason why the temperature of the dirty module is high compared to clean.

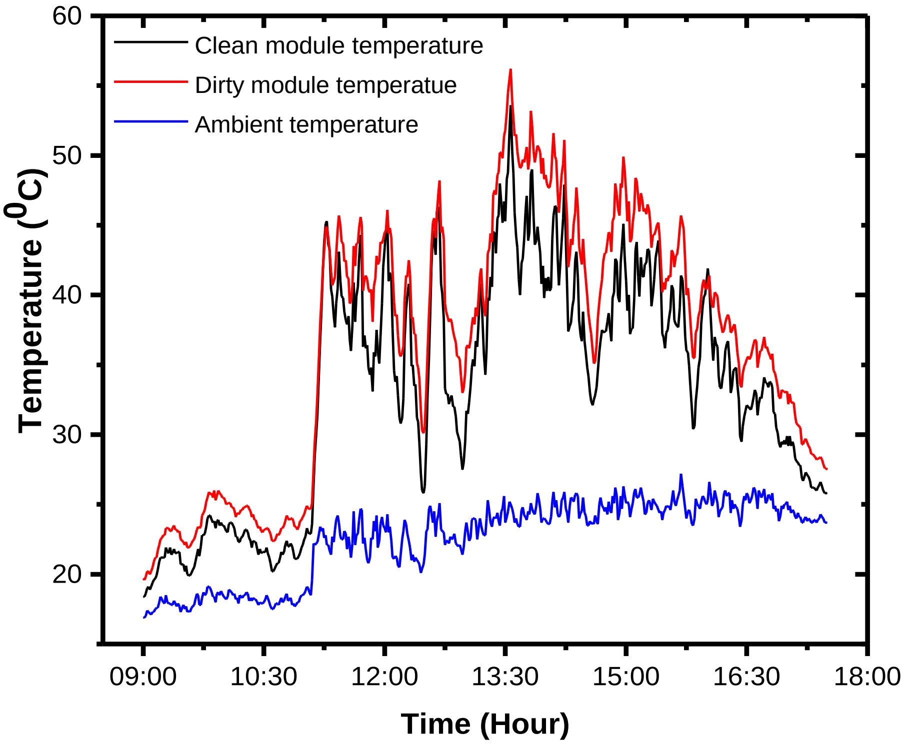


Figure 20: Ambient air and PV module operating temperature.

4.4 Impact of dust on photovoltaic module performance

The impact of dust from manufacturing and mining industries on solar PV performance was assessed based on its type, particle size and distribution over the lower edge of the inclined at three different solar irradiances (720 W/m^2, 800 W/m^2, 900 W/m^2). Not only that but also chemical composition on each tested dust samples as well were studied. It was found that the results revealed on the measurements conducted were much dependent on the types of dust itself, particles size, and elemental compositions as well as the distribution over the module surfaces.

4.4.1 Dust sample characterization

Optical characteristics of dust are associated with the elemental composition. Dust reflectance ability is due to the existence of mineral components which accelerate light reflectance from visible range towards shortwave infrared with 1.4 µm to 1.9 µm absorption band (Rashki, 2012). Presence of mineral elements in the dust sample may influence light reflectance while others may tend to behave with opaque properties means they can altogether avoid light to pass through it. The opaque properties are due to small particles, i.e. iron, which may be composed within the dust sample (Cierniewski & Kuśnierek, 2010).

In this study chemical composition analysis was done by using XRF and CNH analyzer machine whereby the tested samples were indicated to have some mineral elements like Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, N, C and H (Fig. 21). It was determined that carbon (C, 31%) was the dominant mineral element in coal and (C, 22%) was also observed to dominate aggregate dust. Moreover, calcium (Ca, 26%) and (Ca, 23%) was determined to be the principal mineral element in organic fertilizer and gypsum industry dust respectively, while silicon (Si, 19%) was observed to be a dominating mineral element in aggregate dust. Furthermore, the analysis showed that sulfur (S, 13%) was contained in the gypsum industry dust.

The existence of K, S, Cl, and Na reflects the associations of elements with the surface particle, these cause the hygroscopic elements available on the particle surfaces of dust to condense and adhere to the PV module glazing surface and bind together and agglomerate or forming cementing property over module surface. This situation always occurs when soluble materials over the surface particles dissolved under high humidity condition form cementation layer over PV module surfaces which can completely block solar irradiance to pass through. In this study, carbon was observed to high (31%) in dust coal which resulted in high impact in performance reduction followed with aggregate dust which contained 22% of carbon. The higher efficiency degradation from coal and aggregate dust is apparently due to the presence of carbon element in it which can absorb solar irradiance more rapidly. Dust from gypsum is confirmed to have high content of sulphur 13% this is due to additives chemical materials called Potash which contain potassium sulfate, these materials are added during manufacturing of gypsum board.

Occurrences of the high percentage (9%) of phosphate minerals in the sample collected from the organic fertilizer industry are due to the nature of deposits where raw materials are extracted for Minjingu fertilizer production. This is originated from sedimentary rocks which have phosphate content of 15%-20% (Chepkoech, 2015). According to a chemical analysis done for the collected sample also the presence of high content of silicate (Si, 9%) in the dust from organic fertilizer industry was determined.

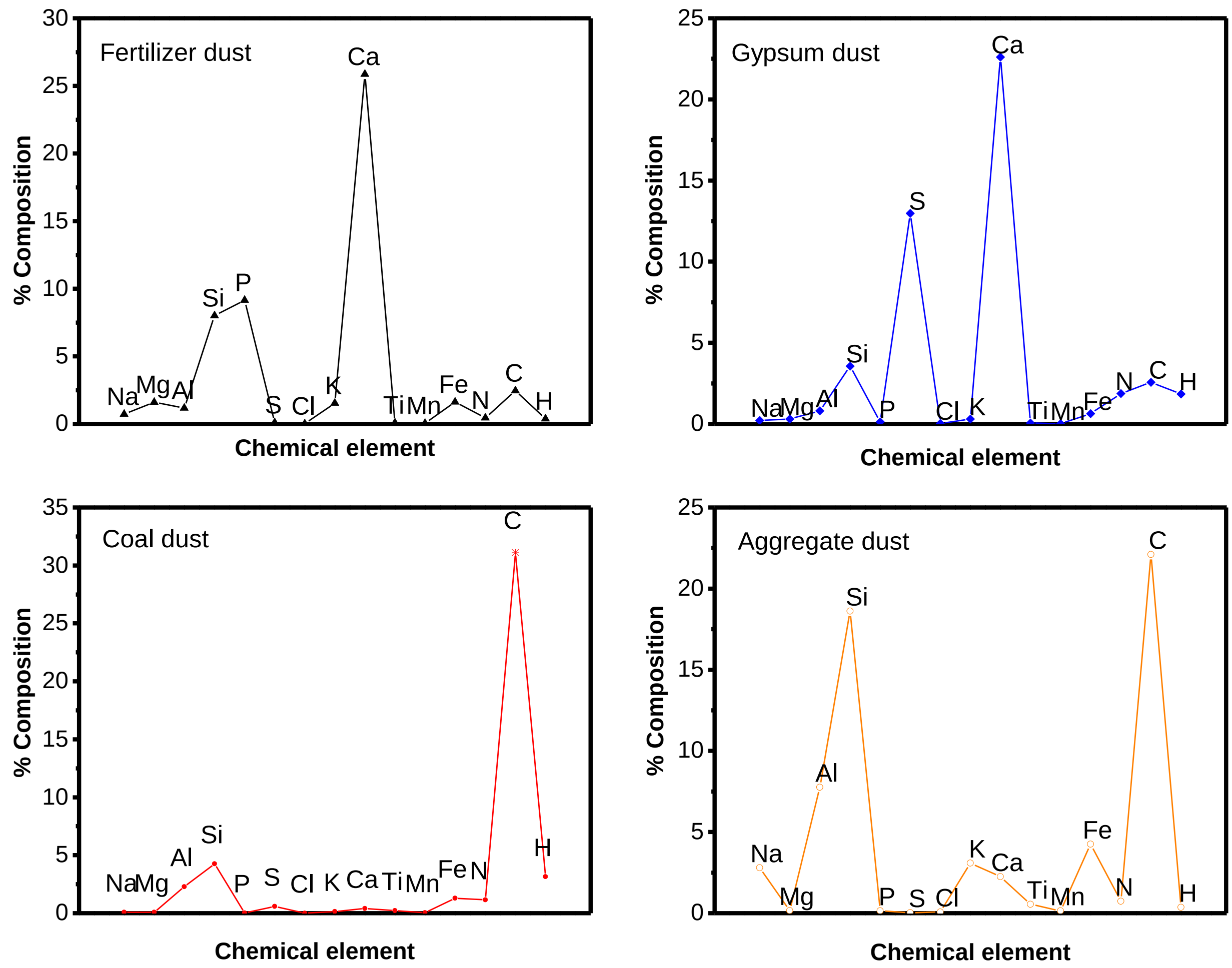


Figure 21: Mineralogical composition for tested samples.

4.4.2 Impact of dust on solar photovoltaic performance under different irradiances

The observation was made when a mass of 10 g from aggregate dust with a particle size of 45-90 µm distributed uniformly over the module before the measurement. The data acquired on operating electrical parameters, voltage, current and power, output both clean and dirty module simultaneously. It was examined that current and power outputs are linearly increasing with solar irradiation intensity as depicted in Fig. 22 (a), (b) and (c). There was a difference in voltage ~0.5 V between clean and dirty module, while dirty module voltage was observed to be higher than that of clean module for the whole experiment. This is due to the hot spot of the shaded cells which always acts as resistance to the other cells therefore according to Ohms law the voltage increases. However, the current drop due to dust deposition was ranging between 1.0 A -1.5 A and output power drop was 20 W -40 W.

Furthermore, the experimental measurement for I-V and P-V for the all tested samples at different irradiance was conducted, but in this paper I-V and P-V curves for the fine particles (20-45 µm) from coal dust are selected to represent (Fig. 23) because fine particles from coal dust have been observed to affect most the module performance compared with the other samples for all different solar irradiances. For 720 W/m^2, 800 W/m^2, and 900 W/m^2 irradiances, the output current (I_{sc}) drop due to dust accumulation was 53%, 56% and 32% respectively.

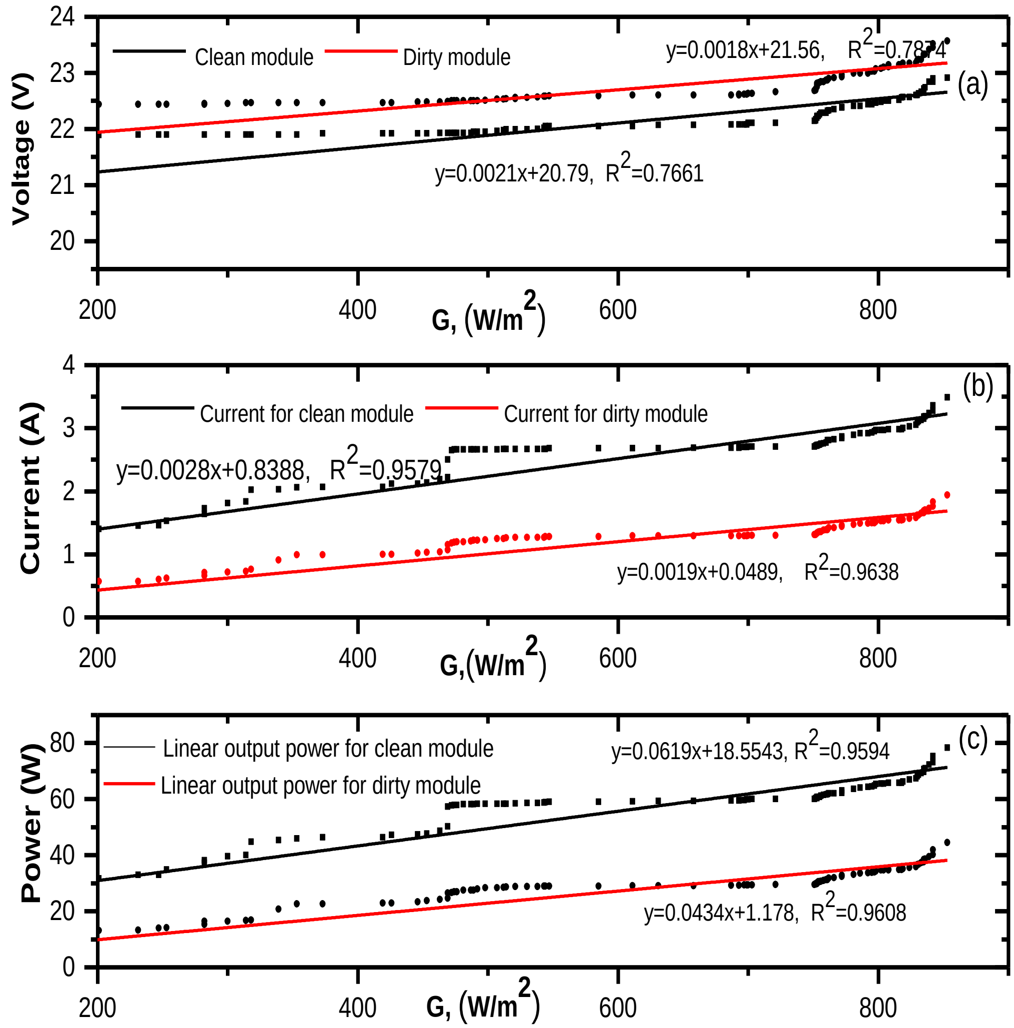


Figure 22: Impact of solar irradiance on operating voltage, current and power output for a clean and dirty module (45-90 µm aggregate dust).

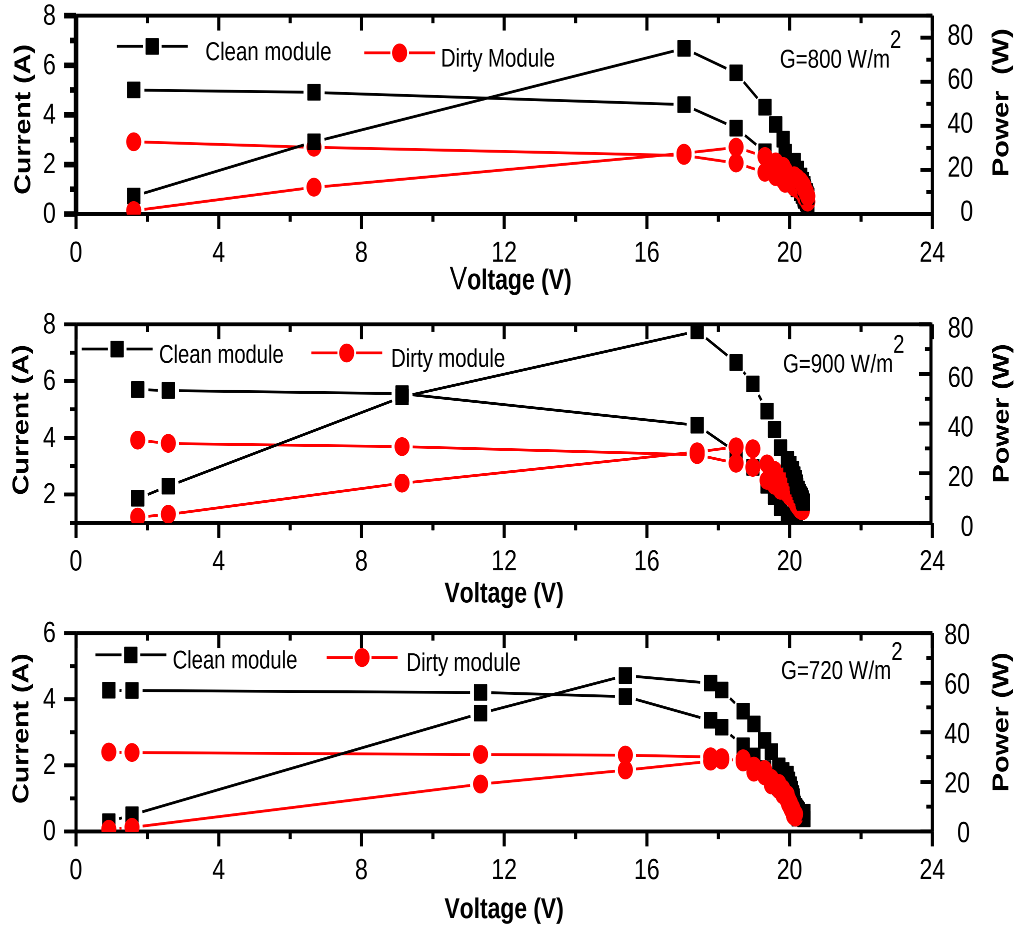


Figure 23: I-V and P-V curves for a clean and dirty module (with 20-45 µm coal dust).

4.4.3 Effect of dust type and particle size on solar module performance

Dust collected from different sources has shown to have a dissimilar impact on performance efficiency reduction on PV module. It was determined that performance losses depend on the dust type. In this study coal dust was observed to have a higher impact on efficiency losses compared to other dust types as depicted in Fig. 24. Furthermore, the study done by Javed, Wubulikasimu, Figgis and Guo (2017) reported that module efficiency losses were progressive increased with the decrease in particle size. In the current study, the fine particles were also observed to bring higher performance efficiency losses in the PV performance as depicted in Fig. 25. Therefore, the results agreed with the earlier author. Hachicha, Al-Sawafta and Said (2019) report that fine particles inhibit solar irradiance from passing through it due to minimal inter-particle gap in between them. Therefore, with the observation stated also by Javed *et al.* (2017), it is the reason for the fine particles to have a significant impact in efficiency loss compared with larger particles. Furthermore, losses also depend on the type of dust applied over PV module, it has being observed that all the tested sample yield different efficiency losses as described in Fig. 24.

The maximum performance efficiency loss was examined to be 64% for coal dust at a particle size of 20 µm-45 µm (fine particle), while 48% was the minimum efficiency loss occurred at 90 µm - 180 µm (large particle) at an irradiance of 800 W/m^2. Moreover, for the same solar irradiance and the same particle sizes, dust from the fertilizer industry revealed to have 29% maximum and 9% minimum efficiency loss. However, for aggregate dust tested at 900 W/m^2, 42% was the maximum efficiency loss occurred at 20 µm -45 µm (fine particle size) while 10% was observed to be the minimum performance loss for 90 µm -180 µm (larger particle size). These are experimental justifications observed in this study. Fine particles have a more impact on performance efficiency loss on PV module as compared to coarse particles.

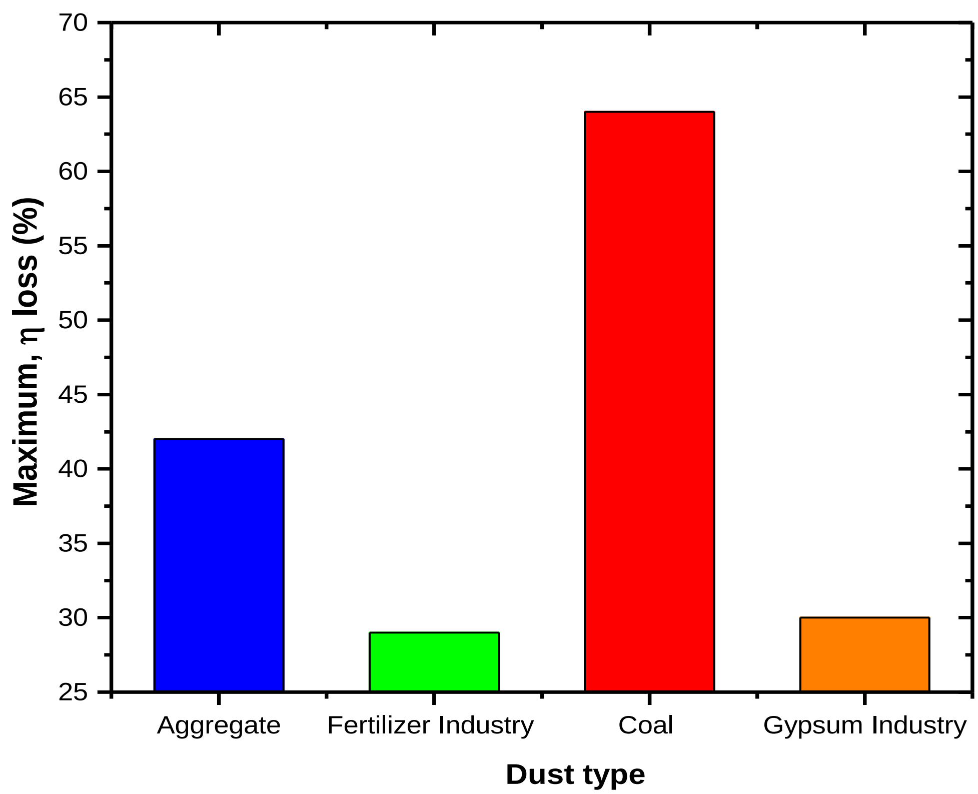


Figure 24: Maximum efficiency loss basing on dust with particle size 20-45 µm.

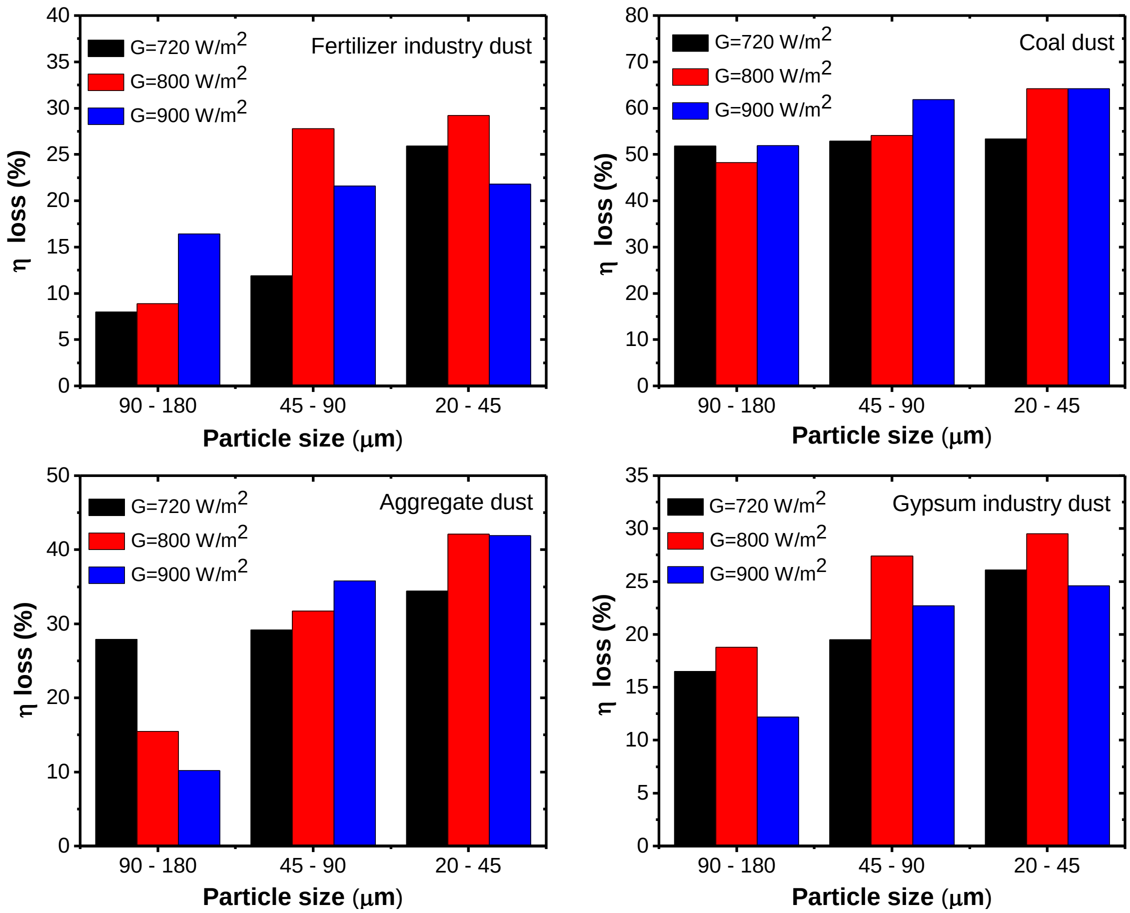


Figure 25: Performance efficiency loss for the four tested dust samples.

4.4.4 Dust type impact on photovoltaic module performance

A significant effect of dust accumulation on module current and voltage output to the fine particles (20-45 µm) for all four dust type is reported in this section (Table 5). It has been examined that dust deposition on PV module does not have a substantial impact on open circuit voltage, this observation is correlated with study conducted by Mostefaoui, Ziane, Bouraiou and Khelifi (2019). Open circuit voltage on dirty module is less than that of the clean module to some extent for all solar irradiance, this may be observed from the last column but one, whereby the ratio V_{oc}(Dirty)/V_{oc}(Clean) remains nearly close to 100% for all the solar irradiance. Dust deposition has a substantial impact on short circuit current generated by the modules. Clean module reliably generates higher output current, the ratio I_{sc}(Dirty)/I_{sc}(Clean) ranges from 43 to 82% for all tested dust type under all solar irradiances as depicted at the last column in Table 5. The disparity in output current reduction may be caused by the fluctuations in solar irradiance received by the module at real-time condition. The stronger effect of dust is seen on maximum power. The ratio of P_{max} (Dirty)/ P_{max} (Clean) varies from 36% to 78% for different types of dust. The P_{max} produced by the coal dusted panel is reduced most drastically, more than twice (by 53%-64%), compared to clean one. Less impact on power results from fertilizer and gypsum dust where the drop in P_{max} occurred by 22-30%. It is interesting to note that the results for V_{oc} differ from that for operating voltage shown in Fig. 21(a), the panels covered by aggregate dust generated slightly higher operating voltage (by ~0.5 V) than clean panel while V_{oc} of the later exceeded by 0.2 V– 0.5 V the V_{oc} of the dirty panel. Therefore, by experimental results, it has been proved that dust settlement over the panel has a more significant impact on current and hence on generated power compared with voltage.

Table 5: P_{max}, I_{sc}, and V_{oc} for a clean and dirty module under fine particles.

G, (W/m^2)	Clean module				Dirty module				P_{max}(Dirty)/ P_{max}(Clean) (%)	I_{sc}(Dirty)/ I_{sc}(Clean) (%)
	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	T_p (^{0}C)	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	T_p (^{0}C)		
					Fertilizer industry dust					
720	65.2	21.1	2.6	31.5	48.3	20.8	1.9	33.1	74.1	74.5
800	41.1	20.6	4.1	32.6	29.1	20.3	3.2	37.0	70.8	76.5
900	84.2	20.5	5.7	43.0	65.8	20.3	4.6	49.0	78.1	80.4
					Aggregate dust					
720	25.4	20.2	1.7	29.6	16.6	19.7	1.2	32.2	65.4	72.1
800	41.1	20.6	2.6	31.8	23.8	20.0	1.7	36.4	57.9	63.1
900	85.9	20.3	5.7	49.9	49.9	19.6	3.7	47.8	58.1	64.0
					Coal dust					
720	62.8	20.4	4.3	42.1	29.3	20	2	49.9	46.6	46.8
800	75.2	20.5	5.0	48.6	26.9	20.1	2.2	48.7	35.8	43.6
900	77.3	20.4	5.7	35.6	27.6	19.9	2.5	39.5	35.7	43.9
					Gypsum industry dust					
720	84.2	20.7	4.5	30.8	62.3	20.5	3.7	32.3	74.0	81.1
800	65.0	20.2	5.0	48.3	45.8	19.8	4.1	51.3	70.5	82.1
900	96.7	20.5	6.3	49.3	72.9	20.2	4.8	50.3	75.4	75.8

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

There are several environmental constraints which affect photovoltaic module performance, dust being among them, which may cause severe output power degradation on the module. Wind speed, relative humidity, module tilt angle, module surface glazing as well as dust properties are the factors which influence dust accumulation over the module surface. The study was conducted to determine the impact of industrial and manufacturing dust deposition on photovoltaic module performance degradation. The outdoor experimental measurement of the polycrystalline module performance was done, impact of dust deposition was determined by attaining operating and maximum power from I-V and P-V characteristic curves of similar modules exposed to the same operating environment (i.e. solar irradiance and air temperature) while one PV module was covered with dust and the other was reserved clean for output comparison. It was examined that the efficiency loss depended on the type of dust accumulated over the panel surface. Maximum efficiency loss of polycrystalline photovoltaic module was observed to be 64%, 42%, 30% and 29% for coal, aggregate, gypsum and organic fertilizer dust respectively, hence coal dust was the most effecting dust sample among the four owing to its highest absorptivity and hence lowest transmissivity. Also, the study proved that the finer dust particles reduced more performance efficiency compared with the larger particles for the all tested samples. Four types of dust, from fertilizer, gypsum, aggregate crusher and coal mines industries, and different particle size were used, whereby the main findings observed in this study were;

i. The coal dust appeared to have a higher impact on performance efficiency loss; that is apparently due to the high content of carbon element which absorbs solar irradiation more rapidly.

ii. Fine particles were observed to have high efficiency loss due to minimal inter-particle distance whereby blocks solar irradiance to pass through it.

iii. Dust deposition has a negligible impact on open voltage (V_{oc}), whereas it has great impact on short circuit current (I_{sc}).

iv. The rise in cell operating temperature affects the output power of the PV module.

v. Drop in current output due to dust deposition lead to power output drop, which causes a huge loss of electrical power and, consequently economic loss to photovoltaic power in consideration to the large-scale solar plant.

vi. Elemental composition analysis conducted for the selected samples determined that carbon content was high in coal dust (C, 31%) and aggregate dust (C, 22%) while calcium amount was high in organic fertilizer industry (Ca, 26%) and gypsum industry (Ca, 23%).

vii. The existence of other mineral elements like K, S, Cl, and Na which was also observed in the tested possesses hygroscopic property under high humidity condition and hence forming a cementing effect to the module surface, and hence it blocks solar irradiance form reaching the module surface.

5.2 Recommendations

Further investigations about dust impact on solar PV module performance can be recommended.

i. Further study basing on the different module tilt angle.

ii. Future study basing on the different PV module type.

iii. Experimental measurement by consideration long time frame under natural dust deposition.

iv. Impact of PV module temperature rise due dust deposition.

v. Comparative study on different environment condition, i.e. clear sky and cloud cover condition, high and low humidity.

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